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THE INFLUENCE OF PLASTIC ANISOTROPY
ON THE LOCALIZED NECKING OF Ti-6Al-4V

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THE INFLUENCE OF PLASTIC ANISOTROPY ON THE
LOCALIZED NECKING OF Ti-6Al-4V

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ABSTRACT. The influence of plastic anisotropy on the localized necking behavior of strongly textured Ti-6Al-4V sheet has been investigated. Tensile tests as well as punch-stretch tests have been performed on strongly textured sheet with either normal or planar anisotropy and with R -values ranging from 0.5 to 12. In uniaxial tension, a high R -value increases the post-uniform elongation but has no significant effect on the uniform elongation. The effects of the R -value on the forming limit diagram depends on the loading path. A high R -value enhances the limit strain at the onset of localized necking in the negative minor strain region, but has little or no effect at plane strain. The dependence of the limit strain on the R -value in the negative minor strain region of the forming limit diagram can be understood in terms of a critical thickness strain criterion. Fracture appears to intervene prior to localized necking in the positive minor strain region of the FLD.

INTRODUCTION. Alpha(bcc)-beta(bcc) or near-alpha Ti alloys in sheet form often exhibit much greater plastic anisotropy than is possible in fcc or bcc alloys. The character of the plastic anisotropy in Ti alloy sheet depends on the specific crystallographic texture but often may be described as: (a) "normal" anisotropy in which the sheet is isotropic in its plane but exhibits a pronounced resistance to through-thickness deformation or (b) "planar" anisotropy in which the sheet exhibits plastic anisotropy in its plane. Ti alloy sheet with normal anisotropy is quite common and results from a "basal" texture [1,2]. If this texture is strong, the sheet will exhibit a high R -value (note: $R = \epsilon_{\text{width}}/\epsilon_{\text{thickness}}$ in a uniaxial tensile test); in this case R is isotropic in the sheet plane and can be much higher ($R > 10$) than that found in steels or Al alloys [1,2]. In contrast, a Ti alloy with a "basal-transverse" texture, or variant thereof, will exhibit planar anisotropy and will possess an R -value which is much smaller ($0.5 < R < 3$) but is dependent on orientation of the major principal strain axis with respect to the rolling direction (RD) [3]. Since strain and strain rate hardening in many Ti alloys does not depend strongly on texture, these alloys provide a convenient means of studying the influ-

ence of plastic anisotropy on mechanical behavior.

Many investigators have studied the influence of plastic anisotropy on certain aspects of the deformation behavior of textured Ti alloy sheet [4-9]. The significant effects that plastic anisotropy exerts on mechanical properties such as the yield stress, ultimate tensile strength, the shape of the yield surface and fracture resistance have been examined and are reviewed in reference [4]. Despite extensive studies of the plastic anisotropy and strength relationships of Ti-alloy sheet, there has been no detailed study of the influence of plastic anisotropy on the large strain deformation and plastic instability process which results in localized necking in Ti-alloys. There have been formability studies [10,11] which have examined certain effects of strain hardening, strain rate sensitivity, strain rate and temperature on the limit strains at the onset of localized necking (forming limits) of Ti and Ti-6Al-4V sheet. However, the sheet materials used in these investigations do not possess strong plastic anisotropy, and the R -values are relatively small ($R = 0.6$ to 1.0). This investigation examines the influence of plastic anisotropy on the process of strain localization and the subsequent local-

ized necking behavior of strongly textured Ti-6Al-4V (Ti-6-4) sheet with either normal or planar anisotropy. Uniaxial tensile testing as well as the punch-stretch testing, as developed by Hecker [12], have been performed in order to determine the effect of the R -value on the development of localized necking as well as on the forming limit diagram (FLD). The Ti-6-4 sheet has been processed to possess a wide range of R -values but with relatively constant strain hardening exponent ($n = d\ln\sigma/d\ln\epsilon$) and strain rate sensitivity ($m = d\ln\sigma/d\ln\dot{\epsilon}$). Thus, the influence of the R -value on localized necking can be separated from that due to strain hardening and strain rate sensitivity (i.e., n and m).

EXPERIMENTAL PROCEDURE. Sheet specimens (1.4 mm thick) of Ti-6Al-4V (Ti-6-4) have been prepared by hot rolling to possess strong basal as well as basal-transverse textures. In processing the basal texture Ti-6-4 sheet with normal plastic anisotropy, 2.5 cm thick plate was cross-rolled at 816°C [1,2] to a final sheet thickness of 1.4 mm. The Ti-6-4 sheet with a basal-transverse texture and planar plastic anisotropy was processed from 6.4 mm thick plate kindly supplied by Del West Associates, and already possessed the desired texture obtained by the thermal cascade rolling method [3]. For the present study, the plate was hot rolled to 1.4 mm sheet by unidirectional hot rolling at 734°C. After specimen machining, the specimens were heat treated at 734°C at a pressure of $<9 \times 10^{-4}$ Pa for four hours and quenched.

Punch-stretching of Ti-6-4 sheet was performed on a Baldwin universal testing machine equipped with a rigid hemispherical punch of 50.8 mm diameter traveling at 0.1 mm/sec. The sheet specimen was held in place by a circular die with sharp grooves and three hold-down hydraulic jacks exerting a 138 MPa hold-down pressure. Following Hecker's punch stretching technique [12], the degree of biaxiality of the state of strain was controlled by varying the width of the specimen and by the lubrication (teflon sheets with silicone grease between them) between the punch and the sheet specimen.

Uniaxial tensile testing was also performed on narrow as well as wide strip specimen at an initial strain rate of

$8 \times 10^{-3} \text{ s}^{-1}$. Tensile specimens used in the determination of material properties (i.e., n , m , and R values) had a 50.8 mm gauge length which was 19 mm in width.

RESULTS AND DISCUSSION. Fig. 1 shows the stress-strain behavior of textured Ti-6-4 sheet. The yield stress and the work hardening behavior of the basal-textured Ti-6-4 are independent of the orientation of the stress axis. In contrast, the basal-transverse texture Ti-6-4 sheet manifests planar anisotropy; the 0.2% offset yield stress and the work hardening rate vary with the orientation of the stress axis as shown in Fig. 1. The effects of crystallographic texture on the tensile yield stress, the work hardening exponent ($n = d\ln\sigma/d\ln\epsilon$), strain-rate sensitivity ($m = d\ln\sigma/d\ln\dot{\epsilon}$) and plastic anisotropy parameter (R) are summarized in Table I. These parameters depend on the orientation of the stress axis in the case of the basal-transverse textured Ti-6-4 but are orientation independent in the basal-textured sheet. An especially noteworthy result is that the influence of crystallographic texture on the work hardening exponent (n) and the strain rate sensitivity (m) is small when

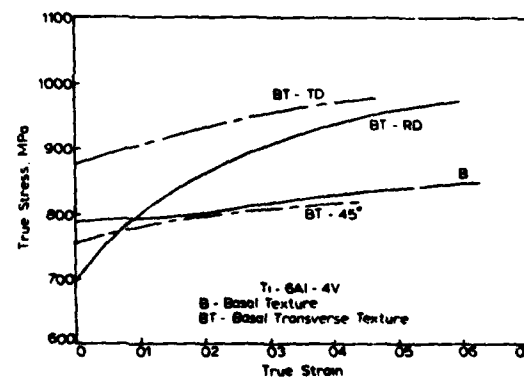


Fig. 1. True stress-true strain curves for Ti-6Al-4V sheet with either a strong basal texture ($R = 12$) or a basal transverse texture ($R = 0.5-2.2$)

compared to the large changes in the plastic anisotropy parameter, R . The n and m values of the textured Ti-6-4 are relatively constant ($n = 0.04-0.06$, $m = 0.012-0.016$), while the R -value changes from 0.5 to 12.

Table 1. Mechanical properties of textured Ti alloy sheet deformed in uniaxial tension at room temperature and a strain rate of 10^{-3} s^{-1} . Note that RD and TD denote tensile axis parallel to the rolling direction and transverse direction, respectively.

Materials		Orientation	σ_y (MPa)	n	m	R
Ti-6Al-4V	basal texture	RD, 45°, TD	780	.052	.016	12
Ti-6Al-4V	basal transverse texture	RD	720	.065	.013	0.5
		45°	760	.039	.014	2.1
		TD	875	.047	.012	1.0
Ti-6Al-4V ^[11]	weak texture		965	.065	.016	0.6 - 1.0
Ti-5Al-2.5Sn ^[17]	basal texture	RD, TD	690	.066	.014	12

The strain distributions along the gauge length of a tensile specimen at different stages of deformation have been determined. Tracing the strain histories of several grid elements, the negative transverse strain ($-c_y$) can be related to the axial strain (c_x). As depicted in Fig. 2, a linear relationship exists between $-c_y$ and c_x at strains which are greater than the strain at maximum load but less than the forming limit strain. Fig. 2 indicates that the plane strain condition ($\rho = dc_y/dc_x = 0$) is easily reached at low strain level when $R = 0.5$. As the R -value increases to 2.2 and especially to 12, the plane strain condition becomes increasingly difficult to achieve and occurs at larger strains.

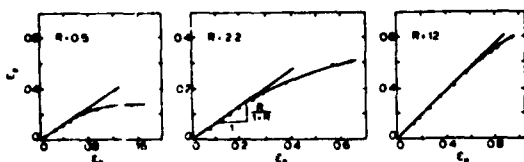


Fig. 2. The dependence of transverse strain c_y on axial strain c_x during uniaxial tensile deformation of Ti-6Al-4V sheet with R -values of 0.5, 2.2, and 12. Note the difference in scales.

The onset of diffuse necking of a sheet tensile specimen occurs at the maximum load and is characterized by a gradual development

* c_x and c_y are also principal strains; therefore $c_x = c_1$ and $c_y = c_2$, except for the 45° case in the basal-transverse textured material.

of a neck with a profile radius that decreases from infinity to a finite value as straining continues. The extent of uniform elongation e_u , measured at the maximum load and by $da/dc = \sigma$, is relatively constant, but the post-uniform elongation e_{pu} increases with the R -value, as indicated in Fig. 3a. This behavior is consistent with the strain distributions in Fig. 2 and with the influ-

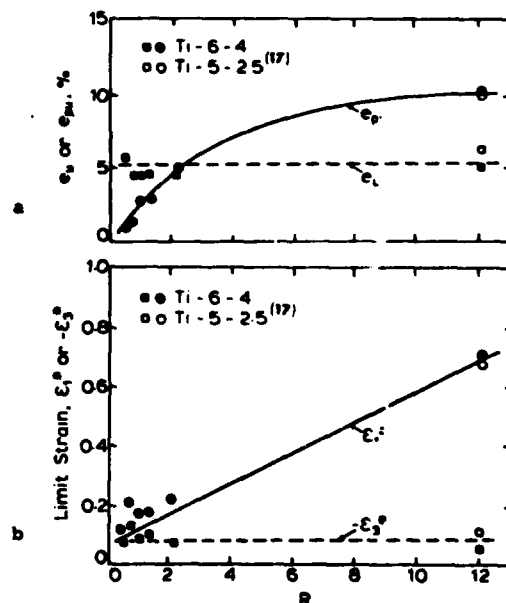


Fig. 3. The influence of R -value on: uniform strain e_u , post-uniform strain e_{pu} , and the limit strain at the onset of localized necking in uniaxial tension as measured in terms of the major principal (axial) strain c_1 or the minor (thickness) strain c_2 .

ence of the R -value on the limiting strain at the onset of localized necking. Fig. 3b shows the limit strain increasing with the R -value. Furthermore, the thickness strain at which localized necking occurs ($\epsilon_3^* = -\epsilon_1^* - \epsilon_2^*$) is approximately constant and is independent of the R -value.

The experimental results indicate that plastic anisotropy, as measured by the R -value, strongly affects the localized necking behavior of sheet deformed in uniaxial tension. Detailed analysis of the strain distribution within the diffuse neck of uniaxial tensile specimens with different R -values reveals that a high R -value extends the diffuse neck profile and tends to delay the attainment of the plane strain condition for localized necking (Fig. 2). The lack of the plane strain condition at the center of the diffuse neck precludes the formation of a localized neck perpendicular to the tensile axis. Instead, the localized neck is formed at an angle inclined to the stress axis and lies approximately along Hill's direction of zero-extension [13]. Fig. 3b suggests that localized necking along Hill's direction of zero-extension follows a critical thickness strain (ϵ_3^*) criterion and that the magnitude of ϵ_3^* does not depend on R (but probably on n and m). Based on this criterion, the increase in limit strain with increasing R -value in uniaxial tension may be therefore interpreted as the result of the difficulty of attaining the critical ϵ_3^* value at a high R -value due to difficult through-thickness slip.

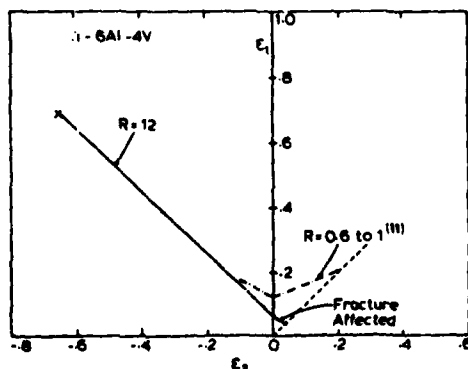


Fig. 4. A comparison of forming limit diagrams for strongly textured Ti-6Al-4V sheet with $R = 12$ and weakly textured Ti-6Al-4V sheet with $R = 0.6-1.0$ from ref. 11.

The forming limit diagram (FLD) of basal textured Ti-6-4 sheet is shown in Fig. 4, while that for the basal-transverse textured sheet is shown in Fig. 5. The forming limit

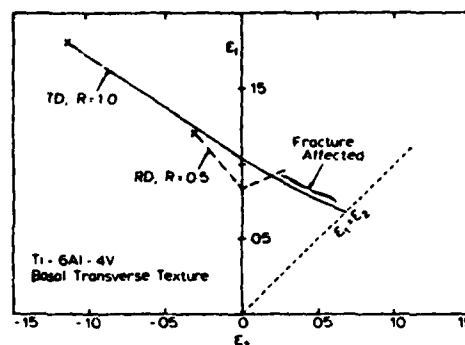


Fig. 5. The forming limit diagrams for Ti-6Al-4V sheet with a basal transverse texture and exhibiting planar anisotropy. Note the difference in scales from Fig. 4.

curves have been constructed based on the criterion proposed by Hecker [12], which considers the strain just outside a visual localized neck as the forming limit strain. The FLD is therefore drawn to lie above the "neck-free" strain and below the necked or fracture-affected strain. Owing to the small fracture strain of the strongly textured Ti-6Al-4V sheet in biaxial tension, the FLD's of both the basal and basal-transverse material appear to be controlled by fracture in the $\epsilon_2 > 0$ region (see Fig.'s 4 and 5). Careful examination (at magnifications up to 50X) of test specimens stretched under balanced biaxial conditions indicates that fracture appears to occur prior to any visible, localized necking. At plane strain, localized necking is just visible but is readily evident in uniaxial tension.

The FLD of basal-textured Ti-6-4 sheet with $R = 12$ (see Fig. 4) is characterized by a large negative minor strain region ($\epsilon_2 < 0$) but a relatively small positive minor strain region ($\epsilon_2 > 0$) which is fracture affected. As an additional basis for comparison, also included in Fig. 4, is the FLD of a Ti-6-4 sheet with a weak texture and $R = 1$ [11] this material does fail by localized necking in the $\epsilon_2 > 0$ region. Fig. 5 shows the FLDs

for the basal-transverse textured Ti-6-4 sheet for the condition when the localized neck is perpendicular to either rolling direction RD or the transverse direction TD. In punch stretching of full-width sheet, localized necking occurs exclusively normal to the TD. It is thus not possible to obtain the balanced biaxial limit strains for necks aligned normal to the RD. A complicating factor is that fracture also affects the FLD for $\epsilon_2 > 0$ in this material. However, in the $\epsilon_2 < 0$ region, the data in Fig. 5 is consistent with the previous results [11] shown in Fig. 4 and obtained from material with a comparably low R-value.

The data in Figs. 4 and 5 indicate that plastic anisotropy does influence localized necking. A high R-value enhances the limit strain at the onset of localized necking in the negative minor strain region of the FLD, and especially at or near uniaxial tension. As discussed previously in regard to behavior in uniaxial tension, the increase in limit strain with increasing R-value in the $\epsilon_2 < 0$ region apparently reflects the difficulty of attaining a critical thickness strain ϵ_3^* at a high R-value due to the difficulty of through-thickness slip.

The R-value appears to have little or no influence on the limit strain at plane strain ($\epsilon_2 = 0$). The plane strain limit strain ϵ_1^* for this study and that previous [11] is roughly constant ($\epsilon_1^* = 0.08 - 0.12$) and independent of the R-value. This experimental observation is consistent with the formability analysis by Neale and Chater [14] which predicts such an independence of the plane strain limit strain on the R-value. The rationale is that there is no change in stress state during plane strain loading [14] and also $\epsilon_1 = -\epsilon_3$ when $\epsilon_2 = 0$; as a result, ϵ_1^* equals the critical thickness strain ϵ_3^* for localized necking at plane strain, and as concluded previously, ϵ_3^* is not affected by the R-value.

It is tempting to interpret Figs. 4 and 5 as indicating the decrease in limit strain with increasing R-value in the biaxial tension region ($\epsilon_2 > 0$) of the FLD. Such behavior would be consistent with the stretch forming analysis of Marciniak - Kuczynski [15] and arguments of Sowerby and Duncan [16]. However, in the present study any conclusions regarding localized necking in the positive minor strain region of the FLD's in Figs. 4 and 5 are precluded by the apparent inter-

vention of fracture prior to localized necking.

SUMMARY. The influence of plastic anisotropy on the localized necking behavior of Ti-6Al-4V sheet has been studied by uniaxial tensile and punch-stretch testing. The 1.4 mm thick Ti-6Al-4V sheet was processed to exhibit either: (a) normal anisotropy ($R=12$) but with in-plane isotropy, or (b) planar anisotropy ($R = 0.5-2.2$). The values of work hardening exponent ($n=d\ln\sigma/d\ln\epsilon$) and strain rate sensitivity ($m=d\ln\sigma/d\ln\dot{\epsilon}$) are relatively constant ($n=0.05$ and $m=0.014$) even though the R-value ranges from 0.5 to 12.

In uniaxial tension, a high R-value enhances post-uniform elongation of the Ti-6Al-4V sheet but has no significant effect on the uniform elongation. A comparison of the strain distribution within the tensile specimens indicates that a high R-value tends to delay the attainment of the plane strain condition at the center of the diffuse neck. However, the thickness strain ϵ_3 at which localized necking occurs in uniaxial tension is a constant ($\epsilon_3 = \epsilon_3^*$) and is independent of R. As a result, the major principal limit strain ϵ_1^* increases with R as it is more difficult to attain the critical ϵ_3^* value at high R-value. The punch stretch results plotted in the form of forming limit diagrams (FLD) show that the localized necking behavior in the anisotropic Ti-6Al-4V sheet is sensitive to loading path. A high R-value increases the limit strain in the negative minor strain region, especially at or near uniaxial tension. However, the R-value has little or no influence on the onset of localized necking at plane strain. These results may be readily interpreted in terms of the influence of both the loading path and the R-value on the attainment of a critical ϵ_3^* value for localized necking to occur. Fracture apparently intervenes prior to localized necking in the $\epsilon_2 > 0$ region of the FLD.

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